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THERMAL RESISTANCE OF METAL-TO-METAL CONTACTS: AN ANNOTATED BIBLIOGRAPHY

SPECIAL BIBLIOGRAPHY
SB-61-39

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Compiled by
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ABSTRACT

44 annotated references on heat transfer through metallic contacts are included. Emphasis is placed on thermal contact resistance in a vacuum. Welded and bonded joints are not included. Most of the information abstracted relates to the technologies of aircraft structural design and nuclear reactor design. The literature sources used were:

1. Applied Mechanics Reviews, 1948-1961
2. Engineering Index, 1940-1961
3. NASA & NACA indices, 1950-1961
4. Nuclear Science abstracts, 1951-1961
5. Lockheed Missiles & Space Co., Technical Information Center Card Catalog

1. Ascoli, A. and Germagnoli, E.

Thermal resistance measurements at the contact between U and Al slabs. ENERGIA NUCLEARE v. 3, n. 2, p. 23-31, 1956.

(In Italian)

Some preliminary results concerning the heat transfer between U and Al slabs are given. The dependence of the thermal resistivity of the contact upon the coupling pressure and the heat flux has been investigated in a wide range of these two parameters.

2. Barzelay, M. E. and Holloway, G. F.

EFFECT OF AN INTERFACE ON TRANSIENT TEMPERATURE DISTRIBUTION IN COMPOSITE AIRCRAFT JOINTS.

NACA TN 3824. Apr 57, 51 p.

Geometrically related structural joints representing typical skin-stringer cross sections were tested under radiant heating to simulate the effects of aerodynamic heating. Temperature histories for 15 2024-T aluminum alloy fabricated specimens and an equal number of integral control specimens were recorded for two different constant heat inputs, ranging from approximately 5 to 40 Btu/(sq ft)(sec). A maximum temperature rise of 450 F was attained in the specimens in 8 to 40 seconds of heating. There was no restraint or external loading applied.

The presence of an interface was found to have a significant effect on the temperature distribution in all geometries tested and thus must be considered in temperature calculations.

Interface conductance values were computed for each of the 15 fabricated specimens. These values ranged from approximately 150 to 1300 Btu/(sq ft)(hr)($^{\circ}$F) with a modal value of 300 Btu/(sq ft)(hr)($^{\circ}$F). Geometry and heating rate were found to have an effect on joint conductance by influencing the temperature distribution and thus the warping of the mating surfaces.

3. Barzelay, M. E., et al

EFFECT OF PRESSURE ON THERMAL CONDUCTANCE OF CONTACT JOINTS. National Advisory Committee for Aeronautics. NACA-TN-3295. May 55, 52 p.

As an extension of previous experimental work further tests were conducted to determine the factors influencing the thermal conductance across the interface formed between stationary plane surfaces of 75S-T6 aluminum-alloy and AISI Type 416 stainless-steel blocks. The types of joints investigated included bare metal-to-metal contact, contact surfaces separated by a good conductor (brass shim stock), and contact surfaces separated by a thin sheet of insulation (asbestos). The average surface roughness of the metal blocks ranged from 10 to 120 microinches root mean square at the interface. The plane areas forming the interface were surface ground to an average flatness of ± 0.0002 inch. The average contact pressure on the interface joint area varied from approximately 5 to 425 psi. The mean temperature of the interface was held to within $\pm$ 5° of 200°, 300°, and 400°F. Heat flows of 7,000 to 80,000 Btu per square foot per hour produced temperature drops across the interface of from less than 1°F to as much as 150°F for some special bare joints and to about 200°F for the insulating types of joints.

4. Barzelay, M. E. and Holloway, G. F.

INTERFACE THERMAL CONDUCTANCE OF TWENTY-SEVEN RIVETED AIRCRAFT JOINTS. National Advisory Committee for Aeronautics. NACA TN 3991. July 57, 23 p.

Twenty-seven structural joint specimens of 2024-T3 and 2024-T4 aluminum alloy consisting of a T-stringer rivited to a 10- by 10-inch skin surface were tested under simulated aerodynamic heating with no external loading applied. Interface thermal conductance was determined from local transient-temperature records. The heat input (approximately 10,000 to 75,000 Btu/(sq ft)(hr)) was held constant during any given test and the duration of heating was from 15 to 50 seconds.

5. Barzelay, M. E.

RANGE OF INTERFACE THERMAL CONDUCTANCE

FOR AIRCRAFT JOINTS. NASA TN D-426. May

60, 63 p.

More than 100 aluminum-alloy and high-temperature-alloy structrual-joint specimens consisting of a stringer joined to a skin surface were tested under simulated aerodynamic heating conditions. Interface thermal conductance was determined from transient temperature records. Most of the specimens were geometrically identical and of the same aluminum alloy in order to take into account the effect of manufacturing variability and of many different types of fastenings; the heat input was nearly constant during any given test; mean interface temperatures as high as 600°F were achieved during the transient heating; and most of the tests were conducted during a period of less than 1 minute.

6. Barzelay, M. E., Tong, K. N. and Holloway, G. F.

THERMAL CONDUCTANCE OF CONTACTS IN AIRCRAFT

JOINTS. National Advisory Committee for

Aeronautics. NACA-TN-3167. Mar 54, 47 p.

Tests were conducted to determine the factors influencing the thermal conductance across the interface between 75S-T6 aluminum alloy and AISI type 416 stainless steel structural joints.

7. Bernard, J. J.

THERMAL CONTACT RESISTANCE OF JOINTS.

Advisory Group for Aeronautical Research

and Development. Rept. no. 212. Oct 58,

16 p. ASTIA AD 221 402. (In French)

A description was presented of an apparatus constructed at O. N. E. R. A., Paris for studying the thermal contact resistance between conductors or between conductors and insulators and the extent to which this varies as a result of the tightening pressure. The measurement conditions differ from those in the various investigations of similar nature previously undertaken mainly in the fact that the thickness of the test piece is not sufficient to permit the

use of thermocouples and all temperature measurements have to be made outside the materials examined. A description is given of the measurement methods applicable in this case and of the relevant instruments used, and results of recent tests are quoted.

8. Boeschoten, F.

On the possibility to improve the heat transfer of uranium and aluminum surfaces in contact.

In PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON THE PEACEFUL USES OF ATOMIC ENERGY. Geneva, Aug. 1955, Vol. 9, p. 208-209.

Several methods for improving the heat transfer between aluminum and uranium surfaces in contact are presented. These methods include applying pressure, gaseous lining, liquid lining and pretreatment.

9. Boeschoten, F. and Van Der Held, E. F. M.

The thermal conductance of contacts between aluminum and other metals. PHYSICA v. 23, p. 37-44, 1957.

The coefficient of heat transfer of a joint between aluminum and aluminum, steel and uranium respectively was measured. The gap between the metal surfaces was filled with air, helium or hydrogen of gas pressures varying between 1 mm Hg and 750 mm Hg. Some oils also were introduced in the joint. The temperature of the joint was about 150 C in all experiments.

It appears that al low contact pressures of several kgf cm^{-2} the heat conduction takes place principally through the gas in the gap, whereas at higher contact pressures the metallic contact spots contribute more and more to the conductance. This is in agreement with the measurements of Weills and Ryder.

Calculation of the thickness of the gap from heat conductance measurements are in rough agreement with roughness measurements with a profilometer and a microscope.

An estimation is made of size and the number of the metallic contact spots, using the theory for electric contacts of Holm and others. From thermal conductance and hardness measurements the average radius of the contact spots is found to be about 30 μ, whereas about 100 of such spots may be found per

per square centimeter at a contact pressure of 35 kgf cm^{-2}.

The contact pressure has not much influence on the size of the contact spots, but their number varies proportionally with the contact pressure. Above a certain value of the contact pressure a confluence of the contact spots takes place and a decrease of their number.

Moreover it seems that the size of the contact spots is independent of the metals by which the joint is formed, a value of about 30 μ being found for a great variety of metals, such as aluminum, uranium, steel, copper, nickel and graphite, under different circumstances, regarding the applied contact. pressure and the size and the shape of the joints.

This independence of the size of the contact spots of the contact pressure, and the materials of the joint, makes it possible to estimate the coefficient of heat transfer of arbitrary metallic joints.

10. Brooks, W. A., Jr., Griffith, G. E. and Strass, H. K.
TWO FACTORS INFLUENCING TEMPERATURE DISTRIBUTIONS AND THERMAL STRESSES IN STRUCTURES. National Advisory Committee for Aeronautics. NACA TN-4052. June 57, 13 p.

The influence of joint conductivity and internal radiation on temperature distribution and thermal stresses has been discussed. Joints of poor conductivity can occur in normal fabrication procedure and greatly alter temperature distributions and increase thermal stresses. On the other hand, internal radiation tends to make the temperature distributions more uniform and thereby relieves thermal stress.

11. Brunot, A. W. and Buckland, F. F.
Thermal contact resistance of laminated and machined joints. ASME TRANS v. 71, p. 253-57, 1949.

Values of thermal contact resistance reported for two types of joints, i.e., joint between two blocks of laminated steel either in direct contact or separated by cement or shims of steel, aluminum or aluminum foil, and joint between two blocks of cold, rolled steel with various surface finishes; resistance as measured amounts to 0.3 to 8 in. of additional material depending on configuration.

12. Brutto, I., Casagrande, I. and Perona, G.
Thermal contact resistance between cylindrical metallic surfaces. ENERGIA NUCLEARE v. 6, p. 532-40, 1959. (In Italian)

A simple method suitable for measuring the thermal contact resistance between cylindrical surfaces is described, and the approximation obtainable is given. Some results on Cu clad by drawing with Al are reported and discussed.

13. Cetinkale, T. N. and Fishenden, M.
Thermal conductance of metal surfaces in contact. In PROCEEDINGS OF THE GENERAL DISCUSSION ON HEAT TRANSFER. London, Institution of Mechanical Engineers. 1951. p. 271-275.

This paper describes measurements of the thermal conductance of joints, formed by pressing together two parallel metal surfaces of the same size. A theoretical expression for the conductance is also developed with the help of Southwell's relaxation method. Direct analytical solution proved impracticable because of the many boundary conditions to be satisfied. Experiments were made with steel, brass, and aluminum surfaces, ground to different degrees of roughness, with air, spindle oil, or glycerol between them, under various pressures. The experimental results agree well with the theory.

14. Coulbert, C. D. and Liu, C.
THERMAL RESISTANCE OF AIRCRAFT STRUCTURE JOINTS. California U. Dept. of Engineering. Rept. no. WADC-TN-53-50. June 53, 45 p. (Contract AF 33(616)-293) ASTIA AD-284 08

An experimental method of measuring the thermal resistance of riveted or bonded lap joints by using a Mach-Zehnder interferometer is described. Results of thermal resistance measurements are presented for 21 typical aircraft-structure joints. These joints were riveted skin and stringer combinations, "Metlbond" joints, and several joints typical of anti-icing duct construction. An average value of thermal resistance for the 12 typical riveted skin stringer

joints was equivalent to 0.00075 inches of air gap with a maximum value of 0.0014 inches air gap. The relative effect of the parameters of rivet pitch, skin thickness, and surface finish was small, and consequently, inconclusive from the limited data obtained. The experimental method developed is simple and suitable for further study or routine measurement of thermal resistance of a variety of lap-joint construction.

15. Davies, W.

Thermal transients in graphite-copper contacts.

BRIT. J. APPL. PHYS. v. 10, n. 12, p. 516-522,

Dec 1959.

The effective surface in contact is assumed to consist of numerous small circular disks which are separated to such an extent that they do not interact electrically or thermally. By applying the differential equation of thermal conduction the distribution of temperature around any of the disks is deduced quantitatively. In the course of the deduction, various approximations are made which appear to be reasonably justified.

Assuming that the current is on for 10^{-4} sec and the metallic surface is free from oxide, an analytical expression for the distribution of temperature is obtained. From this result the greatest rise of temperature in graphite is 50 C. A similar deduction is performed on the assumption that the metallic surface is covered by an oxide film; the greatest rise of temperature in graphite is, in this case, 70 C; this figure, however, is presumably too low because the thermal resistance of the film had not been taken into account. Finally the rate of cooling is deduced assuming that the electrical contact had been broken.

16. Dyban, E. P., Koudak, N. M. and Shvets, I. T.

Investigation of contact heat exchange between

machine parts. IZV. AKAD. NAUK. SSSR OTD. TEKH.

NAUK n. 9, p. 63-79, Sep 1954. (In Russian)

Report on experimental research of parameters affecting the heat flow between metal parts with particular reference to power buckets in turbo-machines. Temperature differential, surface finish, degree of contact pressure, different metals, surface hardness (gross and micro), oxidized coating, plating of surface with soft metals, and the nature of ambient gases were considered systematically for their over-all and reciprocal effect on heat-conduction coefficients.

Tests were run by setting up a stack of two metal blocks with calibrated thermocouples inserted at regular intervals down the height; applying measured electrical heat at the upper end; measuring calorimetrically the heat dissipated at the lower end, and surveying the temperature distribution along the height and across the parting line. Results are clearly presented and experimental accuracy well documented, but researchers declare that their aim for simpler analytical relationships could not be achieved, particularly because of the utter randomness of the areas of direct metallic contact as opposed to the air gaps always present between surface microasperities.

The empirical approach is therefore recommended.

17. Fenech, H. and Rohsenow, W. M.

THERMAL CONDUCTANCE OF METALLIC SURFACES IN CONTACT. Massachusetts Institute of Technology. Heat Transfer Lab. Rept. no. NYO-2136. May 1959, 166 p.

The purpose of the present work is to develop a method for the determination of the thermal conductance of metallic surfaces pressed together. In the first part, a mathematical analysis of a thermal contact is carried-out on on idealized-shape of contact point. The thermal conductance is expressed as a result of this analysis, as a function of the thermal conductivies of the metals pressed together K_1, K_2; the thermal conductivity of the material or fluid filling the void gaps, K_c, the ratio of the real area in contact, A_c to the total area of the contact $A:\varepsilon^2$; the number of contact points per unit area, n; and the volume-average thickness of the void gaps. The case of a uniform heat source in one of the metal making the contact is also treated. It was found that the thermal conductance, was essentially the same as for the previous case (heat generated away from the boundary), neglecting a small correction factor. A recurrence equation is also developed, which expresses the thermal conductance h_n of a contact between surfaces having n types of defects (such as roughness and waviness). The second part of this work outlines a method to determine the physical properties of a contact i.e., the number of contact points, the real area in contact, the volume average thickness of the void, and find their dependence on the pressure applied on the contact. To use this method, two recorded profiles, perpendicular to one another, are needed, for each surface, and a knoop hardness test for the softest of the two metals making the contact. The third part is devoted to the experimental work carried out. It includes; a description of the apparatus and of the method used to determine the conductance; the experimental assertion of the validity of the assumptions made in the theoretical analysis; the application of the method outlined in part two to the case of an Iron-Aluminum contact. Good agreement was found

between the predicted and measured thermal conductance over a range or pressures between 90 p.s.i. to 2,600 p. s. i. The fourth part consists in some further remarks on thermal contacts, the effect of surface oxidation on the electrical and thermal resistance of a contact. Finally values of the thermal contact resistance and their dependence on pressure are calculated, for a given surface state (~150 r.m.s.), and a combination of metals of interest in solid fuels nuclear power reactors (i.e., Uranium metal fuel rods with cladding in Stainless-steel SS-304, Zirconium, Zircaloy-2, Niobium, Beryllium, Aluminum, Magnesium). Plots include the cases where alternatively the void gaps are filled with helium, 50 He + 50 (Xe + Kr), or NaK.

18. Fishenden, M. and Kepinsky, A.

Resistanct to heat transfer in gap between two parallel surfaces in contact. In PROCEEDINGS OF THE SEVENTH INTERNATIONAL CONGRESS ON APPLIED MECHANICS. v. 3, 1948, p. 193-195.

Temperature drops along a steel rod of 2in. diameter sawed in two perpendicular to its axis, were measured under various heat flows. A heat resistance, equivalent to an air layer 0.001 in. or (in a twisted position) 0.002 in. thick, was found. Pressure in the contact was minimal. Convection and radiation losses were accounted for by calculation.

19. Frank, I.

Transient temperature distribution in aircraft structures. J. AERO. SCI. v. 25, n. 4, p. 265-267, Apr 1958.

Author presents analytical solution for conventional symmetrical two-skin-and-channel stiffener configuration reduced to a T by simplifying assumptions: (1) Structural members are thermally thin; (2) joint heat conductance can be represented by analytical convective heat relations; (3) no internal radiant or (nonjoint) convective heat transfer; (4) thermal conduction properties independent of temperature; and (5) heat capacity of stiffener flange in negligible. Heat input (to one surface or symmetrical to both surfaces may be expressed as a polynomial function of time. Validity of assumptions is confirmed by good agreement of theoretical results with experiment.

Method has advantages of analytical solutions: generality, and freedom from extensive numerical computation; it is therefore useful in area of temperature range, beam material thermal properties and beam geometries in which assumptions are justified.

20. Graff, W. J.

Thermal conductance across metal joints.

MACH. DESIGN v. 32, n. 19, p. 166-172,

Sep 1960.

The thermal conductance of the joint, b, is defined as the heat flow per unit area, per unit temperature difference across the joint. It is shown that a dimensionless conductance $b\rho/k\rho$, in which k and ρ are the thermal conductivity and the density of the metal and p is the pressure across the interface, may be correlated with a dimensionless pressure p/B in which B is the Brinell hardness of the metal. Log-log plots are substantially linear. Experimental results collected from published work give a series of lines having approximately the same slope, but these lines are displaced from one another because of differences in surface roughness. A table indicating the degree of roughness to be expected from various finishing methods is given. It is shown how this information can be used in design calculations.

21. Griffith, G. E. and Miltonberger, G. H.

SOME EFFECTS OF JOINT CONDUCTIVITY ON THE

TEMPERATURE DISTRIBUTIONS AND THERMAL STRESSES

IN STRUCTURES. National Advisory Committee for

Aeronautics. NACA-TN-3699. June 56, 62 p.

Temperatures and thermal stresses in aerodynamically heated skin-stiffener combination were calculated with the aid of an electronic differential analyzer. Variations were made in an aerodynamic heat transfer parameter, a joint conductivity parameter, and a ratio of skin width to skin thickness. The results indicate that decreasing the joint conductivity or increasing the heat transfer coefficient increases the peak thermal stresses in the skin and may appreciably increase the peak stresses in the stiffener, whereas the ratio of skin width to skin thickness produces some increase in the peak stiffener stresses but a corresponding decrease in peak skin stresses.

22. Held, W.

Der Waermeuebergang zwischen bearbeiteten

oberflaechen. ALLGEMEINE WAERMETECHNIK

v. 8, n. 1, p. 108, 1957. (In German)

Heat transfer between two finished metal contact surfaces; tests carried out in connection with investigation of thermal conditions in electric machinery; various macroscopically smooth metal surfaces, in which heat contact resistance is determined, as in analogous electrical case, by measurement of heat flow and temperature difference.

23. Holloway, G. F.

THE EFFECT OF AN INTERFACE ON THE TRANSIENT

DISTRIBUTION IN COMPOSITE AIRCRAFT JOINTS.

Syracuse U. 1954 (Thesis).

24. Holm, Ragnar.

Calculation of the temperature development

in a contact heated in the contact surface,

and application to the problem of the

temperature rise in a sliding contact. JOURNAL

OF APPLIED PHYSICS v. 19, p. 361-366, 1948.

In this paper the author extends his work in the field of electric contacts to the case of temperature rise in a sliding contact where the heat is generated by friction. The ideal system proposed is a semi-infinite space limited by a plane surface containing a circular area in which heat is generated at a uniform rate. In the application of this solution to the case of sliding contacts, heat generation in the contact surface is limited at each point to the time of contact. Assumptions are made as to the size of the contact surface based on earlier investigations of the author. Comparisons with experimentally observed temperature rises in bimetallic sliding contacts are also presented. The author was apparently unaware of the paper, "The theory of moving sources of heat and its application to metal treatments," by Daniel Rosenthal (Trans. ASME v. 68, p. 849-865, 1946) which represents a more complete solution of the same type of problem.

25. Holm, R.

Temperature development in a heated contact with application to sliding contacts. J. APPL. MECH. v. 19, p. 369-374, 1952.

The calculation of temperature in and around a contact heated by an electric current or friction is of practical importance. The form and size of contact are generally only roughly known, and approximate solutions only are required. Exact solutions for a few special cases have been previously obtained, but these are complex for computational purposes. Satisfactory approximate solutions, relatively simple to work from, are derived by author for cases of circular and oval heat sources, both stationary and moving in face of a semi-infinite solid. Reviewer is of opinion that notation employed is not always well devised.

26. Jacobs, R. B. and Starr, C.

Thermal conductance of metallic contacts. REVIEW OF SCIENTIFIC INSTRUMENTS v. 10, p. 140-141, 1939.

An investigation was made of thermal conductance between various clean metallic surfaces in a high vacuum. The conductances were studied as a function of pressure and the investigation was limited to good heat conductors. Results are included for gold, silver, and copper as a function of contact pressure at room temperature and at the temperature of boiling nitrogen.

27. Karush, W. and Young, G.

FLOW OF HEAT INTO COATING THROUGH A NARROW STRIP. Chicago U. Metallurgical Lab. Rept. no. AECD-2959. Feb. 29, 1944. Declassified Oct. 16, 1960, 5 p.

The theoretical problem considered is that of cylinder, with internal heat generation, cooled at its outer radial surface through a thin conducting coating and covered on its ends by thin conducting disks through which heat is conducted radially to the cylindrical surface. Owing to these end disks the coating will carry an extra thermal load at the area of junction between the disks and the coating. The extra heat flow through, and temperature rise in, the coating are the subject of the calculations. Two solutions of a problem of this kind are given, one exact and one approximate.

28. Karush, W.

TEMPERATURE OF TWO METALS IN CONTACT.

Chicago U. Metallurgical Lab. Rept.

no. AECD-2967. 22 Dec 44. Declassified 16

Oct. 60, 8 p.

The temperature at the surface of contact of two metals, across which heat is flowing, is considered analytically under certain idealized conditions.

29. Kondo, S.

Thermodynamical fundamental equation for

spherical interface. J. CHEM. PHYS. v. 25,

n. 4, p. 662-669, Oct 1956.

Author derives the fundamental equation for interface and investigates the relation between the position of the Gibbs dividing surface with the superficial density and the "surface tension" by purely thermodynamical means. The surface of tension is defined as that particular dividing surface making the "surface tension" stationary, which later proved to be the minimum. Expressions of the superficial densities are given. Surface tension is then related to the tangential stress on the dividing surface. This stress is found to reach a large negative value at the interface. Reviewer feels that the sign of tangential stress needs clarification, contrary to the convention concerning normal stress.

30. Kouwenhoven, W. B. and Potter, J. H.

Thermal resistance of metal contacts.

WELDING JOURNAL v. 27, p. 515s-520s, 1948.

Report on experiments at Johns Hopkins U. on thermal resistance of steel to steel joint; effects of pressure, temperature and surface roughness; thermal resistance results are reported at two temperature levels for pressures ranging from 195 to 2955 psi; tests at constant pressures and varying temperatures indicate that temperature level has only small effect on thermal resistance.

31. Ling, F. T.

A quasi-iterative method for computing interface temperature distributions. ZEITSCHRIFT FÜR ANGEWANDTE MATHEMATIK UND PHYSIK v. 10, n. 5, p. 461-474, Sep 1959.

Author considers flash temperature problem for semi-infinite body sliding on rectangular contact area protruding slightly above another such body. Staring from known theories, both for stationary and moving heat sources, a singular integral equation of the first kind is set up, under usual assumption of vanishing temperature jump across contact area. Iterative techniques for solving this equation numerically are developed for various ranges of the Peclet number, $R = vl/2\alpha$, where v is the sliding velocity, l the width of the area in the direction of this velocity, and α the thermal diffusivity. Even in the intermediate range where R is of the order of unity, author shows that two iterations suffice for any practical purpose. In the case R = 1, author's result, particularly as regards the maximum flash temperature reached in the contact area, differed only slightly from that obtained according to the approximate technique of Blok (PROC. GEN. DISC. LUBRIC., INSTN. MECH. ENGRS. v. 1, p. 222; London, 1937). To arrive at an exact solution, in the form of a series expansion in Mathieu functions, reviewer suggests to introduce confocal coordinates.

32. Mizushina, T., et al

Thermal contact resistance between mercury and a metal surface. INTER. J. HEAT MASS TRANSFER v. 1, p. 139-146, 1960.

This paper describes a very carefully conducted experiment designed to determine the thermal contact resistance between liquid mercury and a solid. The results indicate a negligible resistance between pure mercury and chromium-plated copper. While it is not the authors' intent to do so, they have also described a simple apparatus which can be used to measure directly the thermal conductivity of conducting materials.

33. Pohle, Frederick V., Lardner, T. J. and French, F. W.

TEMPERATURE DISTRIBUTION AND THERMAL STRESSES IN STRUCTURES WITH CONTACT RESISTANCES. Polytechnic Institute of Brooklyn. Rept. no. PIBAL-557. May 60, 32 p. (Contract AF 49(638)-302)

The temperature distribution in a built-up structure in the form of an I-section composed of cover plates and a web was investigated for the case of a contact resistance at the junction of the cover plates and the web. The temperature-discontinuity condition is discussed relative to proportionality to the time derivative of the web temperature, and a new junction condition is proposed. Graphs of temperature and stresses are presented for the case of constant flux of heat to the cover plates.

34. Schaaf, S. A.

On the superposition of a heat source and contact resistance. QUART. APPL. MATH. v. 5, p. 107-111, Apr 1947.

As two solid bodies are rubbed together, work is done at the rubbing surfaces. This work raises the temperature of the rubbing surfaces and the energy is then transferred by conduction into the body of the solids. This process is idealized as a plane heat source plus surface resistance to heat flow, plus semi-infinite conducting media. It is shown that for several arrangements of heat source and surface resistance, a single boundary condition applies. The appropriate differential equations are set up and solved, making use of Laplace transform methods. General solutions are obtained for the case of constant heat source (as for constant rubbing velocity) and for heat source which is a function of time (as for accelerated rubbing velocity, a projectile in a gun). A few sample computed temperature distributions for a copper block rubbing on steel are shown.

35. Seide, P.

On one-dimensional temperature distribution in two-layered slabs with contact resistance at the plane of contact. J. AERO/SPACE SCI. v. 25, n. 8,

p. 523-524, Aug 1958.

A general solution was developed for both the steady-state and transient state. The actual value of the specific contact resistance still remains as the dominant yet indeterminate variable.

36. Shlykov, Yu. P. and Ganin, E. A.

The thermal resistance of a contact.

ATOMNAYA ENERG. v. 9, p. 496-498, 1960.

(In Russian)

Calculations are presented on thermal conductivity at a contact between rough surfaces at various pressures. The calculated values are in good agreement with experimental data.

37. Simmons, W. E.

HEAT TRANSFER FROM A STAINLESS STEEL TUBE

TO A SURROUNDING WATER COOLED COPPER TUBE

UNDER VARYING AIR PRESSURES AND TEMPERATURES.

Great Britain. Atomic Energy Research Establishment.

Rept. no. AERE-E/R-1205. 9 June 53, 18 p.

Experimental results are given of the heat loss from a vertical heated tube surrounded by a concentric outer tube immersed in a stagnant water bath. The experiments covered a range of temperatures up to 450°C and air pressures in the annulus from atmospheric pressure down to 10^{-2} mm. of Hg. It is shown that the heat transfer is largely by thermal conduction across the air space; natural convection currents do not play a significant part. This agrees with theoretical predictions. Radiation losses have also been separated. In no case did the temperature of the outer tube exceed the water temperature by more than 25°C.

38. Skipper, R. G. S. and Wootton, K. J.

THERMAL RESISTANCE BETWEEN URANIUM AND CAN.

In Second United Nations International

Conference on the Peaceful Uses of

Atomic Energy. A/Conf.15/P/87. 1958, 17 p.

The fuel element cans of most of the current gas-cooled graphite-moderated reactors are not bonded to the uranium fuel. Good contact between can and fuel is ensured by a pressurizing operation during the canning process. The temperature drop at the interface will be small compared to the can-to-gas temperature drop, but an accurate knowledge of it is vital to the fuel element design. The cause of the temperature drop between metal surfaces in contact is discussed, and theoretical methods that have been put forward for evaluating it are considered, including the prediction of the effect of can-filling gas between the surfaces. The effect of mean free path to gap ratio is noted as being important when the filling gas pressure is low. The beneficial results of pre-pressurizing are considered. The experimental approach to the problem is discussed. Experiments which have been carried out using flat plates of uranium and magnesium alloy in contact are described, with special reference to the apparatus designed by the General Electric Company for this purpose. The effects of interface temperature, interface pressure, the choice and pressure of the filling gas, and surface oxidation are considered from the experimental results, and the agreement with theoretical predictions is discussed.

39. Swann, W. F. G.

Concerning thermal junction resistance in

the A. F. Joffe method for measurement of

thermal conductivity. J. FRANKLIN INST.

v. 268, n. 4, p. 294-296, Oct 1959.

The note gives a correction to an elaboration of parts of a previous paper on the same subject (AMR 13 (1960), Rev. 921). The effect of the thermal resistance at the contact interface between the two blocks is discussed in more detail.

40. Swann, W. F. G.

Theory of the A. J. Joffe method for rapid

measurement of the thermal conductivity of

solids. J. FRANKLIN INST. v. 267, n. 5,

p. 363-380, May 1959.

An exact solution is presented for the case where a block of high thermal conductivity is fastened to a block of low thermal conductivity representing

the unknown material. The thermal conductivities and masses of the two blocks are such that one may assume that the block of high thermal conductivity has a temperature which, though time-dependent, is constant throughout the mass, although the temperature may vary throughout the block of low thermal conductivity when its outer surface is suddenly raised to a temperature T_∞ and kept there. If θ is the excess of the temperature at some point over T_∞, the general problem consists in finding θ as a function of distance and time (assuming a two-dimensional heat flow). The two cases where thermal resistance at the contact interface between the two blocks may or may not be present are discussed and relations developed; however, the actual complete expression for θ as a function of distance and time is given only for the case where thermal resistance at the interface is neglected.

41. Tachibana, F.

Thermal resistance of metallic contact parts.

JAPANESE SOCIETY OF MECHANICAL ENGINEERS.

JOURNAL v. 155, n. 397, 1954.

This reference could not be located for verification and abstracting purposes.

42. Vernotte, P.

Extension of Fourier's method to composite systems with resistance to heat flow between certain regions. (Extension de la méthode de Fourier à l'étude des systèmes complexes dans lesquels certains milieux sont séparés par une résistance de passage). C. R. ACAD. SCI., PARIS v. 224, p. 1416-1418, 19 May 1947.

The author first explains the derivative of the known identity

$$m \iiint_V c\rho\varphi\psi\, d\tau \equiv \iiint_V \lambda \left(\frac{\partial\varphi}{\partial x}\frac{\partial\psi}{\partial x} + \frac{\partial\varphi}{\partial y}\frac{\partial\psi}{\partial y} + \frac{\partial\varphi}{\partial z}\frac{\partial\psi}{\partial z} \right) d\tau + \iint_\Sigma h\varphi\psi\, d\sigma$$

upon which is based the general method of calculation of a Fourier expansion for the solution of a cooling problem. In the above expression c, ρ, and λ represent, respectively, the specific heat, density, and conductivity of each medium; h is the coefficient of heat transfer toward the exterior; φ is a continuous function of the co-ordinates such that $\varphi(x, y, z)e^{-mt}$ is a solution of the equation of heat conductors; ψ is an arbitrary continuous function; V is the volume of the system; Σ is the total exterior surface; and $d\tau$, $d\sigma$ are volume and surface elements, respectively.

In the case of contact resistance between bodies, the above identity does not hold, since there is a discontinuity. The author shows that for such a system the right-hand side of the identity contains the additional term

$$\iint_{\Sigma'} \lambda^2 R \frac{\partial \varphi}{\partial n} \frac{\partial \psi}{\partial n} d\sigma$$

when Σ' represents the portions of the surface between two media with resistance R between them. It is stated that either the above identity or the modified form of it serves as a basis for Fourier calculations only by their symmetry in φ and ψ.

43. Weills, N. D. and Ryder, E. A.

Thermal resistance measurements of joints

formed between stationary metal surfaces.

ASME TRANS v. 71, p. 259-67, 1949.

Tests carried out on aircraft engine metals (steel, aluminum alloys, bronze) to determine thermal resistance of dry and oil filled joints between two flat surfaces; apparatus consisted of two test blocks 3 in. diameter times 3 in. long stacked axially in contact with inductively heated copper block at one end and with water cooled copper block at other all between platens of hydraulic press.

44. Wheeler, R. G.

THERMAL CONTACT CONDUCTANCE. General Electric

Co. Hanford Atomic Products Operation. Rept.

no. HW-53598. 13 Nov 57, 13 p. (Contract W-31-109-

eng-52.

Thermal contact conductance literature is reviewed with particular concern about those data that could apply to reactor fuel elements. Contact conductance

values for a number of metal couples are plotted as a function of pressure on the joint so that comparison between the results of the various experiments can be made in consistent units. The use of formulas relating contact conductance to pressure on the joint, hardness of the metals, number of points in actual metallic contact, and the average radius of these contact points is discussed. An observed dependence of thermal contact coefficient on direction of heat flow through joints between dissimilar metals is reported. A theory explaining this effect is proposed.